A Multi-Frequency Inverse Synthetic Aperture Radar (ISAR) Instrument to Explore the Internal Structure of Small Planetary Bodies

Manohar Deshpande

NASA Goddard Space Flight Center, Code 555, Greenbelt, MD

I. Introduction

The planetary scientists and geologists are always interested in understanding constituents of small planetary bodies including asteroids and Near Earth Objects (NEOs). The scientific investigation goals of such planetary missions are (i) to determine the dielectric proprieties of the small-body; (ii) to detect large-size structures (hundreds of meters) and stratifications; (iii) to detect and characterize small-scale irregularities (tens of meters) within the object. One of the important instruments that are used for such studies is very low frequency radar which allows the scientist to measure and analyze radio wave signal which have propagated through all or parts of the target. A detail analysis the reflected and transmitted radio wave signal through the small planetary body will allow the scientists to understand inhomogeneity and will help identify rocks, gaps and voids. From this investigation, it will be possible to answer some fundamental questions of small-bodies science: structural integrity of asteroid? Is it homogeneous, layered or composed of accreted blocks?

Besides its space and planetary applications, RF sounding plays invaluable role in many other engineering applications: Examples: locating human movements behind walls of buildings, rescue operation in an Earth quake area or collapsed buildings. RF sounding is also extensively used for civilian and military applications. The low frequency radar used for RF sounding must be designed differently depending upon its application and requirement.

Figure 1 shows an RRTT (Radio Reflection Transmission Tomography) instrument deployed in an asteroid mission setting and capable of sounding (RF) the internal structure of asteroids and comets to determine their in homogeneity and composition.

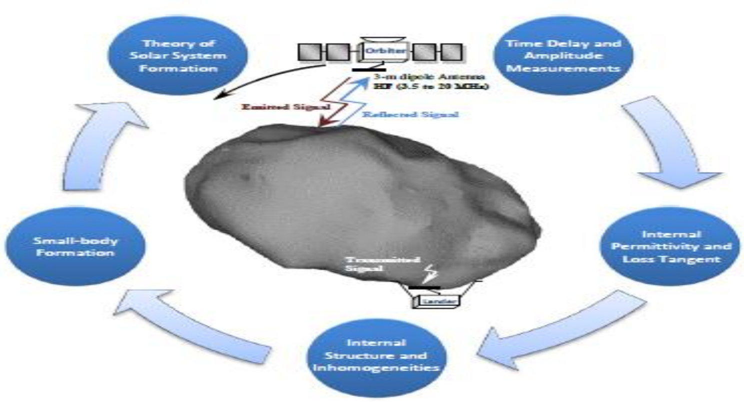

Figure 1: Low Frequency ISAR observing reflected/transmitted radio waves from an asteroid target.

II. Development of Forward & Inverse Mathematical Model for RRTT Instrument

In this section, assuming simple radar model, we develop forward/inverse mathematical models for RRTT instrument. Using the forward model we generate simulated radar data for both reflected and transmitted radio signal. The simulated reflection/transmission data are then used to estimate interior structural image of assumed target.

Forward Scattering Model:

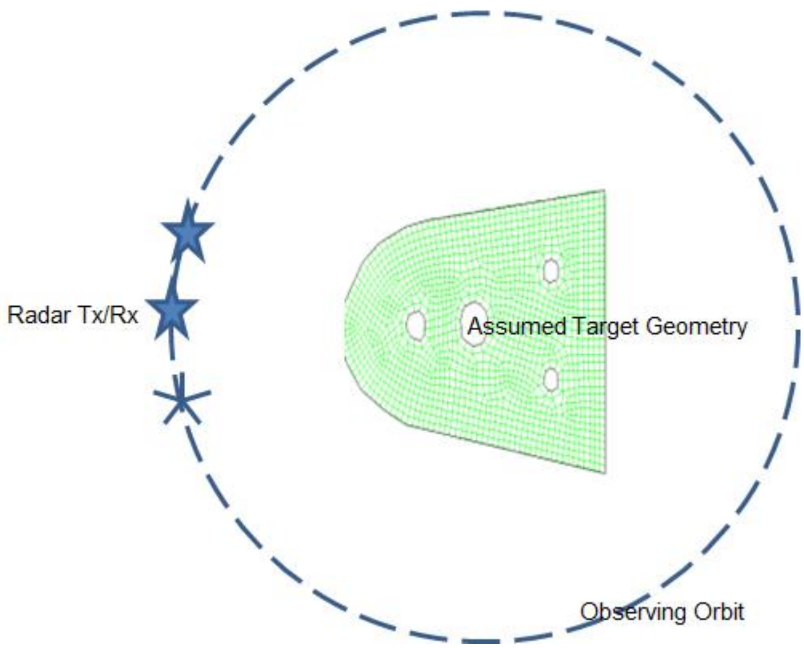

Figure 2: Scattering Model for generating simulated reflection/transmission data

To develop a forward scattering model of a target asteroid, we assume that its topology is known. The interior volume of the shape can then be discretized into appropriate number of tetrahedron cells (Each cell can be assigned different electrical properties). Using the Finite Element Method (FEM, [2]) for the interior region of the target and the Boundary Integral Method (BIM) on the boundaries of the target, electromagnetic scattering from the target for each position of the radar transmitter are estimated. The scattered field calculated at the position of transmitter gives the reflected radio wave signal and the scattered signal at positions other than the transmitter location given transmitted (bi-static). The reflected radio signal (mono-static) and transmitted radio signal for each position of the transmitter in the observing orbit are then calculated to generate simulated radar data.

Inverse Model:

An interior image of a target and its shape/size can be estimated from the reflected and transmitted radio wave signal through the target using appropriate robust algorithms. The reflected/transmitted radio signal data can be obtained through measurements or computer simulation. However, to estimate the system performance before its design, simulated data is preferred. This section describes steps involved in estimating target's image by appropriately processing the simulated data [1,3]. If $[C]_{Mx1}$ is the observed matrix, $[S]_{MxN}$ is the scattering matrix of target, and $[\varepsilon]_{Nx1}$ is the electrical parameter of interior constituents, then the inverse problem is aimed at finding solution to (1)

$$[c]=[S][\varepsilon] \qquad (1)$$

Usually, the number measurements M is much smaller than number of unknowns N. Hence, the exact solution to (1) does not exist. An approximate solution of (1) is attempted, sometime, by using transpose of $[S]_{MxN}$ instead of its inverse as: $[\varepsilon]=[S]^T[c]$ (Linear Back-Projection, LBP). However, the reconstructed image using LBP method is generally blurred. To improve upon the LBP method, it is, sometime, proposed to use iterative Linear Back Projection by using following iterative scheme.

$$[\varepsilon]_{next\_iteration}=[\varepsilon]_{last\_iteration}+\mu[S]^T[c-[S][\varepsilon]_{last\_iteration}] \qquad (2)$$

Since direct inversion of scattering matrix is impossible, sometime, pseudo inverse $[S]^{-1}=[S]^T.[[S][S]^T]^{-1}$ is used to reconstruct the image. However, solving for direct inverse of $[[S][S]^T]^{-1}$ is still an ill-posed problem. A regularization parameter α is introduced as shown $[S]^{-1}=[S]^T.[[S][S]^T+\alpha[I]\}^{-1}$ to overcome this problem.

In this presentation we will present a new and novel approach called Iterative Nonlinear Tikhonov Algorithm with Constraints (INTAC) to estimate sharp images from very limited number of measurements. A brief description of INTAC is given below.

The problem defined by equation (1) can be written in a differential form as

$$[\Delta c]=[\bar{S}][\Delta\varepsilon] \qquad (3)$$

Where $[\Delta c]$ and $[\Delta\varepsilon]$ denotes small changes in the measured values due to small changes in the constituent parameters of the target, and $[\bar{S}]$ represent the sensitivity scattering matrix. Starting from an initial estimation of the unknowns, the proposed nonlinear process consists of the following steps.

(1) Input the current estimate of image $[\varepsilon]^i$ into the forward scattering model and obtain a simulated response and corresponding $[\bar{S}]^i$

(2) Estimate the image correction using

$$[\Delta\varepsilon]^i=[[\bar{S}]^i]^{-1}.[\Delta c]^i=[[\bar{S}]^i]^{-1}.([c]_{measured}-[c]^i) \qquad (4)$$

(3) Correct the image $[\Delta\varepsilon]^{i+1}=[\varepsilon]^i+[\Delta\varepsilon]^i$

The iteration can be terminated when some predefined conditions are met i.e $[\Delta c]$ or $[\Delta\varepsilon]$ reaches some small threshold.

III. Numerical Example

In this section a simple numerical example is illustrated to demonstrate effectiveness of the proposed INTAC reconstruction algorithm..

In this example we consider low frequency radar that can see through the concrete walls of a building. Figure 3 illustrate observation scenario.

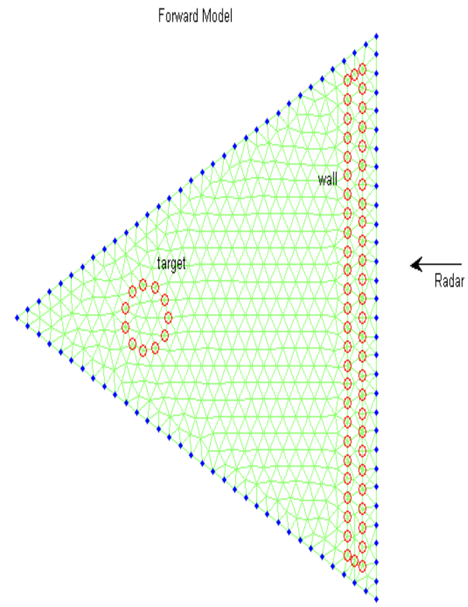

Figure 3: Low frequency radar observing a target behind a concrete wall

It is assumed that radar operates over frequency band of 110-119 MHz bandwidth. It is also assumed that the transmitter position is fixed and the receiver records bi-static scattered signal as it slides across the wall. Using the forward FEM model we generate simulated bi-static scattered data as a function of frequency.

The bi-static scattered data is processed through 2 methods: (1) SAR Processing (2) INTAC Processing. The results obtained using the conventional SAR processing is shown in Figure 4. The results obtained using INTAC is shown in Figure 5.

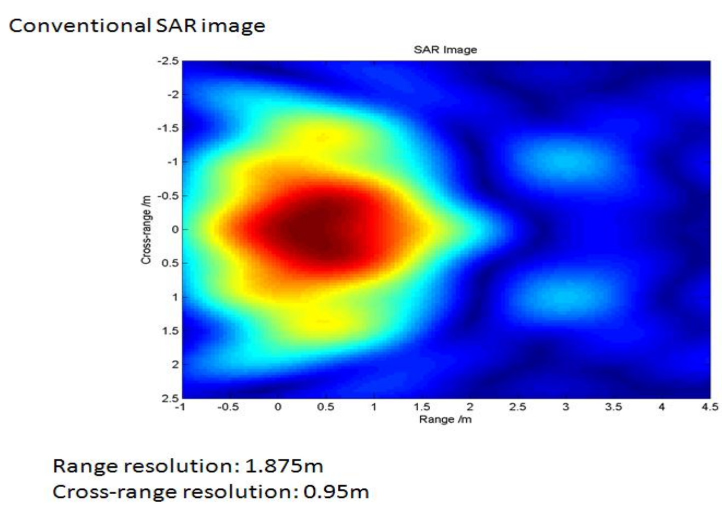

Figure 4: Radio image of structure shown in Figure 3 using SAR Processing

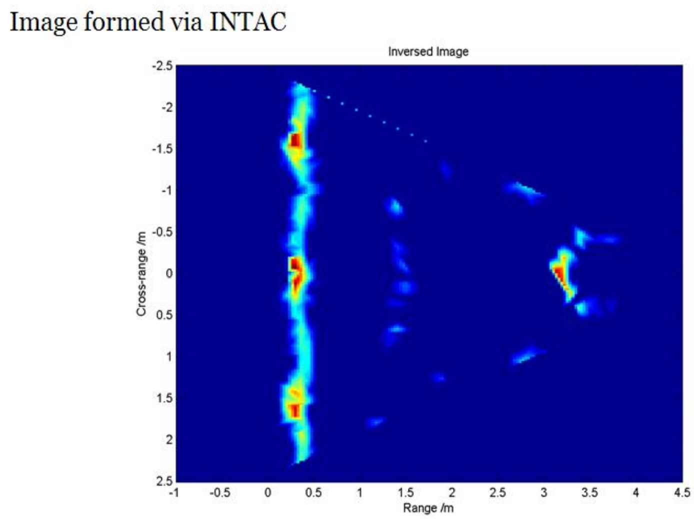

Figure 5: Radio Image of structure shown in Figure 3 using INTAC Process

IV. Conclusions

Numerical models to generate synthetic radar data has been successfully implemented using FEM-BEM method. Using forward scattering model, a superior inverse model known as INTAC has been developed and validated using synthetic radar data. INTAC incorporates a priori knowledge to eliminate uncertainties and require fast forward model for real-time application

V. References

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[3] Li, Y and W Yang (2008): Image reconstruction by nonlinear Landweber iteration for complicated distributions, Meas. Sci. Technol., Vol 19, 094014